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WINGTIPS AND MULTIPLE WING TIPS EFFECTS ON WING PERFORMANCE: THEORETICAL AND EXPERIMENTAL ANALYSES

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ABSTRACT

The purpose of this investigation was to find out how the shape of the wing tip influences the induced drag. The wingtip configurations tested were: blended winglets, raked wingtip, wingtip fence, spiroid winglets and a new configuration called 'triple blended winglets'. The wing geometry data was gathered from the UIUC Database and Airbus website. Simulation was performed at 80 $ms^{-1,}$ which is the take-off speed of the Airbus A380 and Reynolds number of the wing was at 67.12 million, based on the mean aerodynamic chord length, as reference length which was 12.25m. The theoretical analysis was based on the computational fluid dynamic Package (Phoenics), where flow boundary conditions were applied and the discredited Navier-Stokes equations were solved numerically. It was found out that all the wingtip and winglet designs were able to reduce the induced drag and improve the aerodynamic performance. It was also shown how each wingtip configuration works differently and is effective at specific ranges of flight. At cruise angle of attack, raked wingtip offered the highest C_L/C_D improvement (8.24 %), followed by the wingtip fence (7.64 %). This indicated that raked wingtips are suitable for long ranges and wingtip fence is suitable for mid-long range. At take-off angle of attack, the triple blended winglets offered the highest C_L/C_D improvement (8.89 %). This result indicated that triple blended winglets are suitable for short range. It was shown that Spiroid winglets work better than blended winglets at both cruise (6.75 % for Spiroid winglets and 6.51 % for blended winglet) and take-off (7.64 % for Spiroid winglet and 6.94 for blended winglets) and should be considered in the future.

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INTRODUCTION

The wings of an aircraft are the main components that enable the aircraft to fly. In order for the wing to be able to generate lift, the pressure of the lower surface of a wing must be greater than the pressure at the higher surface. Since air always flows from a region of high pressure to a region of low pressure, a potentially dangerous phenomenon occurs. The air flows from the lower to upper surface by making an end run around the wingtip. This twisting flow is known as the wingtip vortex and is a problem in the aircraft industry. The wingtip vortices create additional drag, reducing the performance of the wing. Aircrafts have to create more energy fuel to overcome this effect and therefore consume more fuel. In the 1970's, the demand for commercial aircrafts increased rapidly. The price for aviation fuel therefore escalated. Up to this time, airlines and aircraft manufactures have looked at many ways to improve the operating efficiency of their aircraft. One very visible action taken by the commercial airframe manufacturers and operators to reduce fuel consumption is the modification of an aircraft's wingtip, to reduce aerodynamic drag due to wingtip vortices. These tip modifications reduced fuel consumption from the beginning to the end of a flight. These wingtip modifications were also available for retrofit to older aircraft. Traditional winglets were mainly used at that time. According to the U.S. House of Representatives Armed Services Committee in Report 109-452, winglets offered 5 to 7 percent reduction to fuel consumption depending the distance. Scientists have been trying to design new types of wingtips to further improve the aerodynamic performance of aircraft's wings.

WINGTIP VORTEX DEVELOPMENT

According to Sheldon I. Green (1995), [1], tip vortices are produced wherever a lifting surface terminates in a fluid. A wing moving through air generates lift by producing low static pressure above the wing and high pressure below it. The large pressure difference between the wing pressure and the suction accelerates the fluid around the wingtip. As a result, a tip vortex is produced as shown in Figure 1, reproduced from page 428 of book Fluid Vortices written by Sheldon I. Green in 1995.

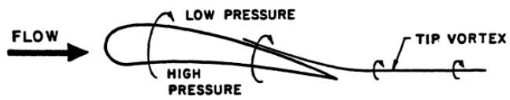

Figure 1: Formation of a tip vortex along a wing

The wing tip vortices generate a downwash of air behind the wing which is very strong near the wing tips and decreases toward the wing root as shown in Figure 2. As a result, the lift is reduced and the drag is increased.

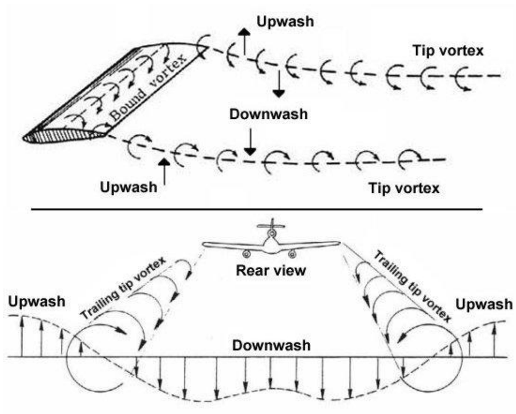

Figure 2: Downwash created by trailing vortices

The angle of attack of the wing is increased by the flow induced by the downwash, resulting, in a downstream-facing component to the aerodynamic force acting over the entire wing. This downstream component of the force is known as induced drag. Induced drag has been a major problem in the aircraft industry. In order to overcome this induced drag, aircraft need to generate more thrust and thus burn more fuel, [2],[3],[4], and [5].

METHODOLOGY

Cartesian coordinate system was used. The control volume was a wind tunnel. The dimensions of the control volume were; 80 m in x, 40 m in y and 80 m in z. A velocity inlet and outlet was created as shown in Figure 3. The inlet velocity was set to 80 ms-1 (Mach number 0.24) since this is the take-off velocity of Airbus A380, [6]. Turbulence was simulated using standard k-ε model, [7], [8], and [9]. The model was chosen as it does not need special arrangement near the boundary and the flow does not contain large eddies in the immediate vicinity of the winglets to warrant a full Reynolds stress model.

The Reynolds number of the wing, R_e was therefore 67.12 million based on a mean aerodynamic chord length of 12.25m.

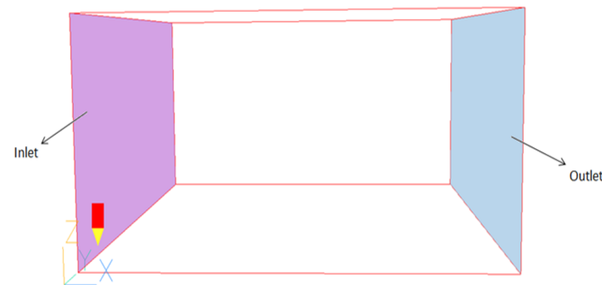

Figure 3: Creation of velocity inlet and outlet

A grid convergence study was made to compare the results between fine and coarse grids. The number of cells near the wing was increased and was made to be finer. This was achieved using PHOENICS' auto-mesh control parameters, more precisely the cell factor and the cell expansion power. Figure 4 describes the meshing strategy adopted. All simulations were run under this condition.

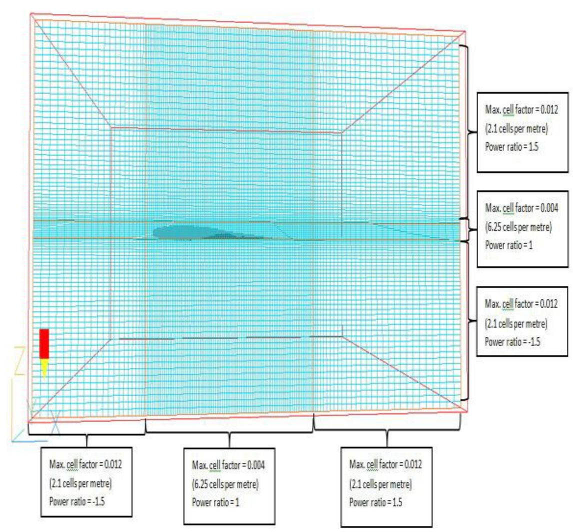

Figure 4: Creation of grid using different cell factor and power ratio to increase the accuracy of velocity and pressure contours

RESULTS AND DISCUSSION

When an aircraft is on the ground, the angle of attack is around 4°. Most aircraft take-off at an angle of attack of around 12 degrees and cruise at an angle of attack of around 4° to 6°. Therefore the analysis was focused on angles of attack 0°, 4° and 12°. An increase in C_L/C_D makes increases the aerodynamic performance of an aircraft and hence contributes to fuel savings.

The wing tips that are used for this investigation are the wingtip fence, blended winglet, spiroid winglet and triple blended winglets and these are shown in Figure 5 below.

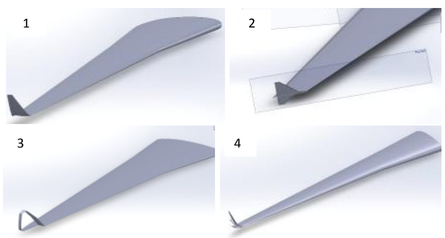

Figure 5: (1) wingtip fence, (2) blended winglet, (3) spiroid winglet and (4) triple blended

WING PERFORMANCE AT 0 DEGREE ANGLE OF ATTACK

Table 1 shows the aerodynamic coefficients of the wingtip configurations at 0 degrees angle of attack and Figure 6 shows the velocity contours.

Wingtip configuration	C_L	C_D	C_L/C_D	% C_D	% C_L/C_D
No wingtip	0.0472	0.0124	3.82	-	-
Wingtip fence	0.0381	0.0128	2.96	-3.87	-22.35
Raked wingtip	0.0433	0.0114	3.80	7.93	-0.40
Blended winglet	0.0379	0.0129	2.92	-4.71	-23.40
Spiroid winglet	0.0361	0.0139	2.59	-12.54	-32.10
Triple blended winglets	0.0319	0.0135	2.37	-8.96	-38.03

Table 1: Aerodynamic coefficients at 0 degrees angle of attack

Since the wingtip vortices are weak at 0 degrees angle of attack, their effect on the flow is minimal. Referring from Table 1, it can be deduced that none of the wingtip configurations offer any improvement in C_L/C_D. Compared to other wingtip profiles, the raked wingtip is the most efficient when the aircraft is on the ground, from the point of view of drag reduction and increased C_L/C_D ratio. The spiroid winglet and triple winglet are the two least efficient. This is due to their shape which increases the drag.

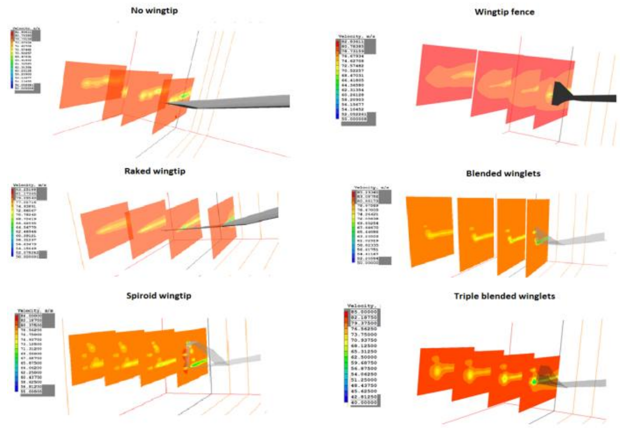

Figure 6: Velocity contours at 0 degrees angle of attack

WING PERFORMANCE AT 4 DEGREES ANGLE OF ATTACK

Table 5 shows the aerodynamic coefficients of the wingtip configurations at 4 degrees angle of attack. Figure 7 and 8 shows the velocity and pressure contours respectively.

Wingtip configuration	C_L	C_D	C_L/C_D	% C_D	% C_L/C_D
No wingtip	0.2280	0.0246	8.87	-	-
Wingtip fence	0.2257	0.0236	9.55	3.82	7.64
Raked wingtip	0.2355	0.0245	9.60	0.21	8.24
Blended winglet	0.2218	0.0235	9.45	4.49	6.51
Spiroid winglet	0.2282	0.0241	9.47	1.94	6.75
Triple blended winglets	0.2228	0.0240	9.28	2.33	4.62

Table 2: Aerodynamic coefficients at 4 degrees angle of attack

WINGTIP FENCE

With wingtip fence, the value of C_L is 0.2257 and C_D is 0.0236 and the ratio C_L/C_D is 9.55. The increase of C_L is because the wingtip fence generates non-planar lift by the use of stable vertical flow from its small 'delta shape'. An area of high pressure increase around the wingtip fence is as shown in Figure 8. This provides stability to the wing. The flow separates just downstream of the leading edge and rolls-up into a vortex due to the high leading-edge sweep-angle of the upper fence. Lower fence also produces a vortex, but smaller in size because the angle of sweep approaching the lower tip fence is reduced. The upper vortex and the lower vortex curl around each other to form a single vertical elliptic vortex, as shown in Figure 7. This is how wingtip fence reduces the drag.

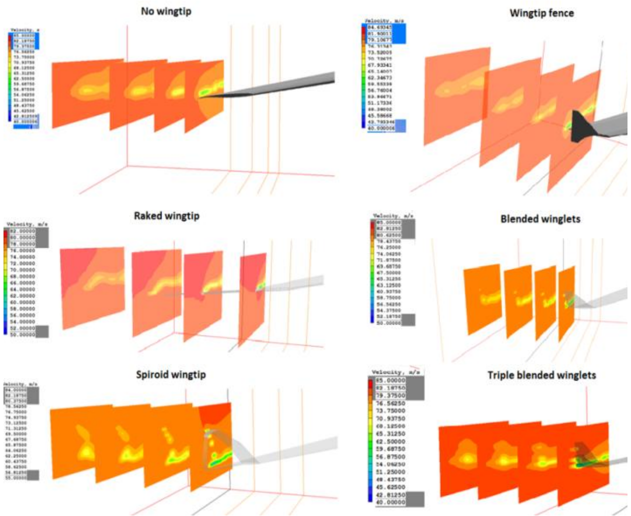

Figure 7: Velocity contours at 4 degrees angle of attack

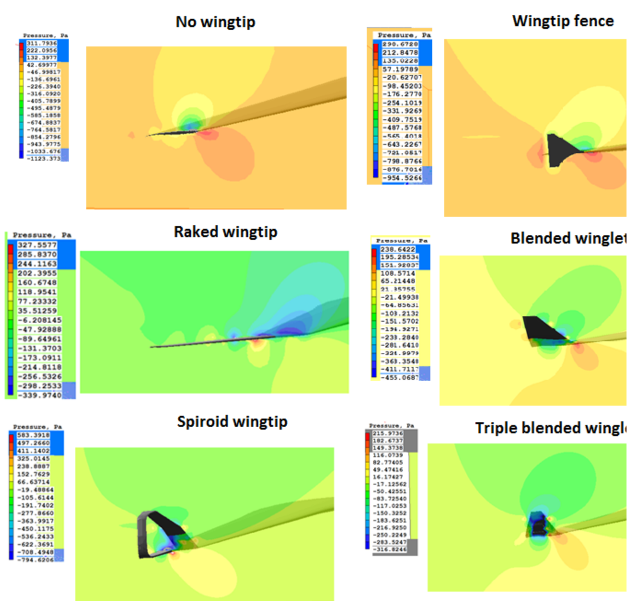

Figure 8: Pressure contours at 4 degrees angle of attack

RAKED WINGTIP

With raked winglet, the value of C_L is 0.2355 and C_D is 0.0245 and the ratio C_L/C_D is 9.60. The extreme angle of sweep reduces leakage from the high pressure region below the low pressure region above the wing as shown in Figure 8. This is how lift is increased. The extreme angle of sweep also creates a small vortex which drags the main vortex caused by the wing, reducing its intensity and hence a reduction of drag, [10], [11], and [5]. The shape of the combined vortices can be seen in Figure 6. It can also be seen that the downwash formed behind the wing is weakest when compared to the other wingtip configurations.

BLENDED WINGLET

With the blended winglet, the value of C_L is 0.2218 and C_D is 0.0235, and the ratio C_L/C_D is 9.45. The increase in lift can be attributed to the positive traction component of the winglet. The high difference in pressure between the upper and lower section of the winglet is what provides this effect. An area of high pressure around the winglet is clearly seen in Figure 8. This area extends to the tip of the winglet and thus provides stability to the wing.

The decrease in drag is due to the shape of the vortices formed as shown in the velocity contour plot in Figure 7. The shapes of the contours have transformed and have become more vertically elliptical in nature. The flow is forced to travel up and around the winglet and two smaller vortices are formed instead of one. These elliptical shaped vortices travel towards the tip which dissipates the energy from the wing-tip vortex which results to a decrease in drag, [5], [12], and [13].

SPIROID WINGLET

With the Spiroid winglet, the value of C_L is 0.2282 and C_D is 0.0241 and the ratio C_L/C_D is 9.47. Similarly to blended winglets, the increase in lift is due to the positive traction component of the winglet. The high difference in pressure between the upper and lower section of the winglet provides the additional lift as shown in the pressure contour in Figure 8.

The flow is forced to travel up around the winglet, resulting formation of several small vortices around the winglet. These vortices curl with the vortex formed at the tailing edge, thus lowering its intensity. This is how drag is reduced. The vortices formed as shown in the velocity contour plot in Figure 6.

TRIPLE BLENDED WINGLETS

With Triple blended winglets, the value of C_L is 0.2228 and C_D is 0.0240 and the ratio C_L/C_D is 9.28. The triple blended winglet works the same way as the conventional blended winglet. The difference here is that three smaller vortices are formed instead of two.

Referring from table 2, it can be clearly seen that the raked wingtip offers the highest C_L/C_D improvement (8.24 %), followed by the wingtip fence (7.64 %). This explains why the raked wingtip is suitable for long range aircraft since most aircraft cruise about this angle of attack. The wingtip fence is also more efficient than the spiroid (6.75 %) and blended winglet (6.51 %). The triple blended winglet (4.62%) is the least efficient compared the other configurations.

WING PERFORMANCE AT 12 DEGREES ANGLE OF ATTACK

Table 3 shows the aerodynamic coefficients of the wingtip configurations at 4 degrees angle of attack. Figure 9 and 10 shows the velocity and pressure contours respectively.

At 12° degrees angle of attack					
Wingtip configuration	C_L	C_D	C_L/C_D	% C_D	% C_L/C_D
No wingtip	0.5660	0.1020	5.55	-	-
Wingtip fence	0.5693	0.0980	5.81	3.94	4.70
Raked wingtip	0.5720	0.0988	5.79	3.09	4.29
Blended winglet	0.5712	0.0963	5.93	5.62	6.94
Spiroid winglet	0.5794	0.0970	5.97	4.90	7.65
Triple blended winglets	0.5811	0.0962	6.04	5.71	8.89

Table 3: Aerodynamic coefficients at 12 degrees angle of attack

Figures 9 and 10 show how all the wingtip configurations work in the same way as described previously to improve the wing performance. At 4 degrees angle of attack, the raked wingtip is the most efficient. However, at 12 degrees angle of attack, the raked wingtip is no longer able to reduce the intensity of the vortex formed, as it did at 4 degrees angle of attack and the downwash is much stronger. The triple blended winglets produce the weakest downwash, as shown in Table 3 at the 12 degree angle and hence are the most efficient wingtip configuration at this angle of attack.

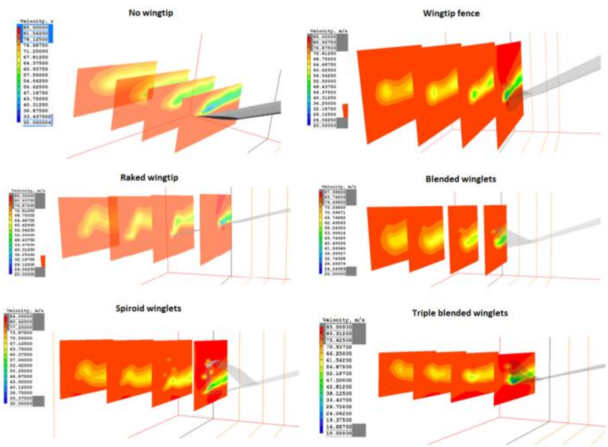

Figure 9: Velocity contours at 12 degrees angle of attack

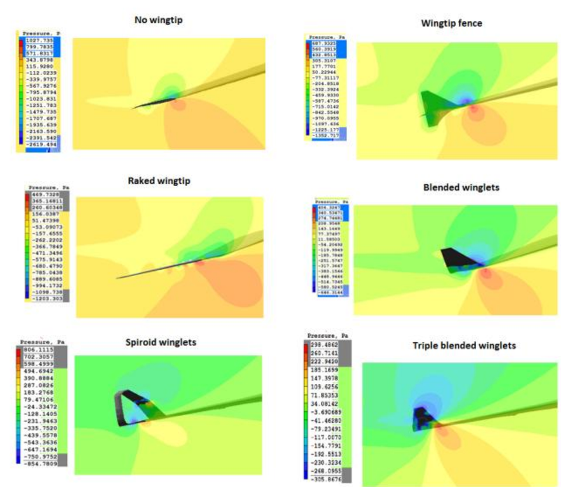

Figure 10: Pressure contours at 12 degrees angle of attack

Referring from table 3, it can be seen that the triple blended winglets offers the highest C_L/C_D improvement (8.89 %), followed by the spiroid winglet (7.64 %). Therefore the triple blended winglets are suitable for short range aircraft which require frequent take-off manoeuvres. Wingtip fence offers an improvement of C_L/C_D of 4.70%. Therefore wingtip fence is suitable for mid-long range. One more important result here is that the spiroid winglet (7.64 %) is more efficient that the blended winglets (6.94 %). They are both used in mid range. The spiroid is on overall slightly more effective than blended winglets at both cruise and take-off.

AERODYNAMIC PLOTS

The C_L vs. α, C_D vs. α and C_L/C_D vs. α curve for all wingtip configurations are shown in Figure 11, 12 and 13 respectively. Table 4 shows the maximum C_L/C_D ratio ($(C_L/C_D)_{max}$) and corresponding angle of attack at $(C_L/C_D)_{max}$ for the wingtip configurations.

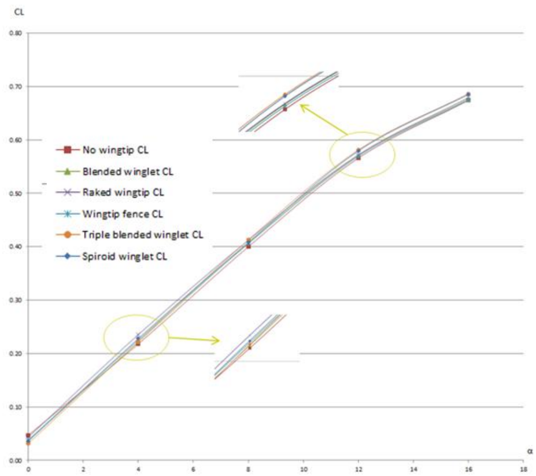

Figure 11: C_L vs. α curves for wingtip configurations

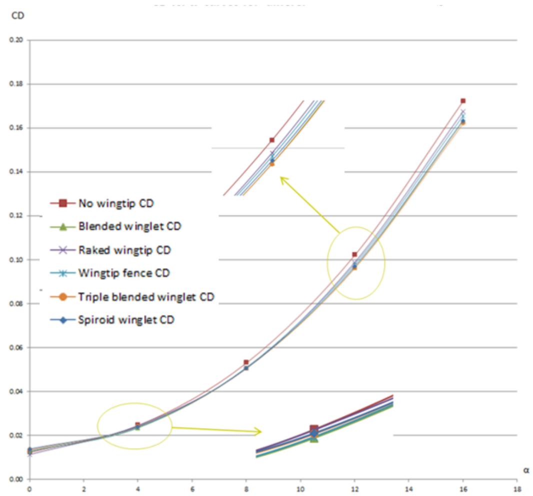

Figure 12: C_D vs. α curves for wingtip configurations

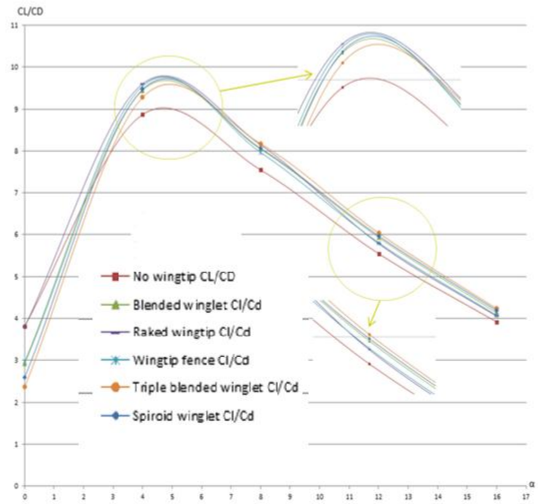

Figure 13: C_L/C_D vs. α curve for wingtip configurations

Wingtip configuration	$(C_L/C_D)_{max}$	Angle of attack at $(C_L/C_D)_{max}$	% $(C_L/C_D)_{max}$
No wingtip	9.03	4.71	-
Wingtip fence	9.75	4.72	7.97
Raked wingtip	9.78	4.70	8.31
Blended winglet	9.68	4.69	7.31
Spiroid winglet	9.73	4.73	7.75
Triple blended winglets	9.58	4.95	6.20

Table 4: $(C_L/C_D)_{max}$ and corresponding angle of attack at $(C_L/C_D)_{max}$ for wingtip configurations

The cruise angle of attack, that is, angle of attack at $(C_L/C_D)_{max}$ is roughly about 4.7 degrees for this wing model. The wingtips do not greatly affect the angle of attack at $(C_L/C_D)_{max}$ as shown in table 4. As mentioned earlier, at cruising condition, wingtip fence has the highest C_L/C_D ratio (8.31 %) followed by wingtip fence (7.97 %). Referring from Table 4, it can be seen that blended winglet has highest ratio (6.94 %) at take-off compared to wingtip fence (4.7 %) and raked wingtip (4.29%).

To sum up the raked wingtip offers the highest aerodynamic improvement at cruising, which makes it suitable for long ranges and the blended winglet offers the highest aerodynamic improvement compared to wingtip fence and raked wingtip, which makes it suitable for medium range. This validates the theory as mentioned in the literature review.

Figure 14 summarise the effectiveness of the wingtip configuration according to the range.

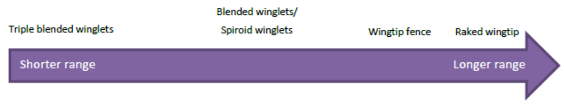

Figure 14: Wingtip configuration effectiveness with respect to range

CONCLUSION

It has been shown that a wing without any wingtip devices produces the most induced drag. All the wingtip and winglet designs are able to reduce the induced drag and improve the aerodynamic performance. They work differently and are effective at specific ranges of flight. Raked wingtips work the best for very long ranges since they have the highest C_L/C_D ratio at cruise angle of attack. However, at higher angles of attack, as the intensity of the vortices get higher, raked wingtips are no longer able to reduce the downwash. On the other hand, the new type of configuration designed, the 'triple blended winglets' are able to reduce this. Hence, at higher angle of attack, the triple blended winglets configuration is the most effective. Whereas, at lower angles of attack, it is not as effective as other wingtip configurations. Hence, the triple blended winglets are suitable for low ranges only. The aerodynamic improvement that wingtip fences, blended winglets and Spiroid winglets offer is somewhere between raked wingtip and triple blended winglets, which makes them more suitable for medium range. At cruise, wingtip fence offers better aerodynamic improvement compared to blended winglets and Spiroid winglets. This makes it best for mid-long range. For medium range, both blended winglets and Spiroid winglets are effective. However, it was shown that Spiroid winglets work better than blended winglets at both cruise and take-off. It can be concluded that the Spiroid winglet design must be considered over blended winglet design in the future. Also, the triple blended winglets configuration must be considered for low range aircraft.

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